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IMPROVED PLATE-FRAME HEAT EXCHANGE REACTOR WITH SERIAL CROSS-FLOW GEOMETRY

Technical Field

The present invention relates generally to heat exchange systems and more particularly plate-frame heat exchangers.

Background

Plate-frame heat exchangers are commonly-employed to provide relatively compact devices with low-pressure drop. Such devices are typically deployed in weight/volume critical applications such as automotive air-conditioning evaporators, gas turbine recuperators, fuel cells, and liquid-liquid industrial heat exchangers. Because these applications are sensitive to both heat exchanger size and pressure drop through the fluid passages, typical plate-frame heat exchangers have a series of individual heat exchanger cells arrayed substantially in parallel (i.e. each cell (hot fluid side and cold fluid side) has the same temperature distribution as every other cell in the stack of cells comprising a completed heat exchanger)).

Because of the success of the plate-frame approach to heat exchanger design, it has been widely adapted to chemical reactions requiring temperature control, especially those that require close temperature control because of product selectivity or

are strongly endothermic or exothermic and require rapid heating and cooling.

A common example of considerable importance is steam reforming of hydrocarbons and alcohols (This reaction involves the reversible chemical conversion of methane and water into carbon monoxide and hydrogen). This reaction is highly endothermic, and typically requires large amounts of catalyst to promote the reaction. A complication of the use of the plate-frame reactors is that the effectiveness in exchanging heat between the cooler reformate stream and the hot combustion products plays a strong role in determining the thermal or thermodynamic efficiency of the reforming system. Effectiveness factor is defined as the temperature that occurs in the fluid undergoing the maximum temperature change divided by the difference between the highest and lowest temperatures in the heat exchanger.

Current technologies have focused on plate-frame reformers having an array of small reactors massively in parallel to each other. This design is far more compact, lighter and less expensive than tubular-type reformers which are common in the industry. However, such reformers have three major drawbacks.

First, massively parallel construction leads to low flow velocity (and corresponding Reynolds number) and low laminar flow. This drawback is critical because lower laminar flow reduces heat transfer rates and reduces reactant mixing in the reactor structures, which along with the Reynolds

number are factors in sizing the reformer. Hence, a lower Reynolds number requires a larger reformer, which adds to the cost of the reformer system.

Second, manifolding in the massively parallel construction may be fairly complex. This complexity may cause poor fluid distribution with "dead zones", where little flow occurs, which reduces heat exchange effectiveness.

Third, controlled internal release of any one reactant is very difficult as the short reaction zone is only accessible from either end of the plate. This point is particularly important if the heat exchanger structure is to be used as a catalytic burner. Catalytic burning on the heat exchanger walls improves heat transfer locally by obviating convective heat transfer from the gas phase to the wall because the catalysts are located on the wall itself. Unfortunately, if fuel or oxidant levels are not controlled, the catalytic burning can occur at too high a rate, causing local increases in metal temperature referred to as hot spots. Hot spots significantly weaken the structure and may cause mechanical failure. Because of this fact, systems with catalytic burning on the wall must use exotic materials and dilute combustion gases to lower temperatures to an acceptable level, which negatively impacts both cost and efficiency.

It is thus highly desirable to design a plate-frame reactor that combats the three critical drawbacks of the massively parallel system.

Summary of the Invention

It is thus one object to create a novel method of arranging the elements of a plate-frame heat exchange reactor with serial cross-flow geometry.

The new arrangement has several advantages over the massively parallel reactor systems. First, the new arrangement increases the Reynold's number of the flows to greatly improve the heat transfer characteristics and reactant mixing characteristics of the reactor, thereby reducing the reactor size by half or more. Second, the new arrangement allows for constructing reactors where reactant addition is possible at many distributed points along the serial flow using simple mechanical features in order to control hot spots or other undesirable chemical reactions. Third, the new arrangement greatly simplifies manifolding of the flows and reduces the number of distinct components required in the heat exchanger. Fourth, the heat exchanger plate geometry is not constrained to long narrow ducts to create high aspect ratio counterflow designs.

Other objects and advantages of the present invention will become apparent upon considering the following detailed description and appended claims, and upon reference to the accompanying drawings.

Brief Description of the Drawings

Figure 1 is a perspective view of a fuel processing assembly with a plate-frame heat exchange reformer having serial cross flow geometry according to the present invention;

Figure 2A is a header sheet for use in a preferred embodiment of the present invention;

Figure 2B is an interleaved sheet for use in a preferred embodiment of the present invention;

Figure 2C is an exploded view illustrating the stacking of the cells according to a preferred embodiment of the present invention;

Figure 2D is an exploded view illustrating the stacking of the cells, wherein the fin sheets have been added to the header sheets, according to a preferred embodiment of the present invention, wherein the fin sheets are placed into the header sheets;

Figure 3 illustrates the flow pattern of feed gas and burner exhaust utilizing serial cross flow through a plate frame reactor according to a preferred embodiment of the present invention;

Figure 4 illustrates the flow pattern of feed gas and burner exhaust utilizing purely serial cross flow through a plate frame reactor according to another preferred embodiment of the present invention; and,

Figure 5 illustrates the flow pattern of feed gas and burner exhaust utilizing a combination of

serial cross flow and parallel flow through a plate frame reactor according to another preferred embodiment of the present invention.

Description of the Preferred Embodiment(s)

Referring now to Figure 1, a fuel processing assembly 10 which forms a portion of a typical fuel cell power plant is depicted. The assembly 10 includes a plate frame heat exchange reformer 12 for converting hydrocarbon fuels into hydrogen that is used by electrochemical fuel cells (not shown) to generate electricity. The reformer 12 is primarily comprised of a series of stacked cells 14. Each stacked cell 14 is comprised of a header sheet 16 and an interleaved sheet 18. The reformer 12 has an intake port 20 for receiving feed gas, typically gasoline, natural gas, or some other type of hydrocarbon, from a reservoir (not shown) and an outlet port 22 for removing the heated reformed feed gas from the reformer 12. The feed gas may also comprise any combination of water, oxygen, nitrogen, carbon monoxide, carbon dioxide, hydrogen, and partially reacted fuel. The reformer 12 has a burner inlet port 24 for receiving heated burner exhaust gas and/or a partially or wholly unreacted mixture of fuel and oxidant (hereinafter referred to as burner exhaust gas) and a burner outlet port 26 for removing cooled burner exhaust gas from the reformer 12. The flows of the feed gas and burner exhaust through the embodiments of the present invention are described in more detail below.

Figure 2A illustrates a header sheet 102 according to a preferred embodiment of the present

invention having a central zone 106, a fin sheet 108, and a series of manifold ports 110. The central zone 106 houses the fin sheet 108 or roll-formed fins that form the extended heat transfer surface. The fin sheets 108 may contain louvres 121 or other features to control the flow across their surfaces as is known in the art. While the preferred embodiment depicts fin sheets 108, it is contemplated that other types of heat transfer surfaces, such as pin fins, metal foam, or corrugated sheets may be used as heat transfer components. The header sheet 102 may also contain a locator tab 114. While not depicted in Figure 2A, the manifold ports 110 may be on any or all sides of the header sheet 102. As shown in Figure 3 below, they will be depicted as 110f representing manifold ports located on the front side 102f of the header sheet 102, 110l for the ports located on the left side 102l of the header sheet, 110r for ports located on the right side 102r of the header sheet, and 110b for ports located on the back side 102b of the header sheet 102. Further, the number and size of manifold ports 110f, 110r, 110l and 110b may vary according to the flow strategy of the system that they are used in. In addition, these manifold ports 110 may be augmented by similar passages (not shown) for the conveyance of yet additional reactant fluids or diluents.

Figure 2B illustrates the thinner interleaved sheet 120 according to a preferred embodiment of the present invention. The interleaved sheets 120 form the common heat transfer interface between the fluids. The interleaved sheet 120 may also contain a locator tab 126. Similar to the header sheets 102, the interleaved

sheets 120 contain interleaved manifold ports 122. While not depicted in Figure 2A, the interleaved manifold ports 122 may be located on any or all sides of the interleaved sheet 120. As shown in Figure 3, the interleaved sheets 120 may have front side interleaved manifold ports 122f, right side interleaved manifold ports 122r, left side interleaved manifold ports 122l, and/or back side interleaved manifold ports 122b. Further, the number and size of the interleaved manifold ports 122r, 122f, 122l, and 122b may vary according to the flow strategy of the system they are placed in. Finally, the interleaved sheets may contain louvres 121 or other features to control the flow across their surfaces as is known in the art.

Figure 2C and 2D illustrate an exploded view of alternating copies of the header sheet 102 and interleaved sheet 120 of Figures 2A and 2B. Each pair of header sheets 102 and interleaved sheets 120 form a single cell 104. The assembly of a purely serial flow heat exchanger 100 reactor from the bottom would proceed by rotating subsequent sets of header sheets 102 and interleaved sheets 120 90 degrees counterclockwise from the previous pair. For simplicity, note the location of the locator tab 114 of the header sheet 102 relative to the location of the locator tab 126 of the interleaved sheet 120 in a single cell 104. Figure 2D illustrates the fin sheets 108 contained within the central zone 106 of the header sheet 102.

The header sheets 102 and interleaved sheets 120 may be joined through many techniques that are well

known in the art, including soldering, brazing, and adhesive joining. For high temperature applications, brazing is the preferred method.

A catalyst material (not shown) may be affixed to the reactor 100 by applying a thin layer of catalytic material to the structural substrate material. This might comprise a layer of high surface area gamma-alumina powder with a dispersed catalytic metal adhered to a superalloy or stainless steel structure. The open manifolds 110, 122 possible in the serial flow design allow for uniform application of such "washcoat" catalyst layers because they allow uniform access to the complex fin sheets 108 upon which the bulk of the catalyst is disposed. Methods of applying such catalyst layers are well known in the art.

Referring now to Figure 3, the flow patterns of feed gas and burner exhaust through the reformer 100 having purely serial flow geometry according to a preferred embodiment is depicted.

Cool feed gas enters the reformer 100 through an inlet port 101, or plenum. The feed gas then proceeds between a top sheet 117 and top header sheet 102a within a topmost cell 104a that defines a first reformer section 103a. The top sheet 117, as depicted, is a sealing sheet and contains no manifold ports. However, the top sheet 117, in alternative embodiments, could contain the inlet port 101. The feed gas then enters front manifold port 110f, flows through the front interleaved manifold port 122f of the interleaved sheet 120. The feed gas then flows back through the

next adjacent reformer section 103 to back manifold port 110b, flows through back manifold port 110b and back interleaved manifold port 122b and into the next adjacent reformer section 103. The feed gas then flows back through the next adjacent reformer section 103, enters the front manifold ports 110f, flows through front interleaved manifold 122f, and into the next adjacent reformer section 103. This process continues through the stack of reformer sections 103 until the heated and fully reacted feed gas reaches the outlet port 105. The number of cells 104 in the reformer 100 may vary greatly depending upon the requirements of the system. For example, flow rate, catalyst activity, and peak temperature are factors in determining the number of cells 104 within the reformer 100.

At the same time, heated burner exhaust enters the reformer 100 through a burner inlet port 107. The burner inlet port 107 is located at the bottommost cell 104b, while the feed gas inlet port 101 is located at the topmost cell 104a. Of course it is understood that the opposite could be true, wherein the feed gas inlet port 101 is located in the bottommost cell 104b and the burner inlet port 107 is located in the topmost cell 104a.

The burner exhaust flows through a first burner section 105a as defined between a bottom section 109 a bottom sheet 102b. The exhaust then enters the left manifold ports 110l, flows through left interleaved manifold ports 122l, and into the next adjacent burner section 105. The exhaust then flow through the next adjacent burner section 105 and into

the right manifold port 110r, through the right interleaved manifold port 122r and into the next adjacent burner section 105. This process continues through the stack of burner sections 105 until the cooled exhaust gas reaches the burner outlet port 111.

As seen in Figure 3, the flow patterns of the feed gas and the burner exhaust flow flowing through adjacent reformer sections 103 and burner sections 105 are locally perpendicular with respect to each other, although the overall flow geometry is counterflow. This is known as serial cross-flow geometry. In addition, heat is exchanged through the interleaved-sheets 120. In this way, the feed gas is heated and eventually reacted and the burner exhaust gas is cooled within the reformer 100. To aid in the heat exchange, the interleaved sheets 120 may be provided with heat transfer enhancement in the form of louvres 121 or separate fin sheets 108.

In addition, a second inlet port 180 may be added to direct a secondary flow of feed gas into the reformer 100. The second inlet port 180 is added between one of the header sheets 102 and one of the interleaved sheets 120 defining a cell 104 and introduces feed gas to the reformer section 103. Similarly, a second burner inlet port 190 can be added to direct a secondary flow of burner exhaust gas, fuel, oxidant, or diluent into the burner section 105. In this way, the heat exchange, and corresponding chemical reaction in the reformer section 103 and burner section 105, can be more closely controlled in order to avoid hot spots and limit unwanted chemical reactions. Of

course, the number of second inlet ports 180 and second outlet ports 190 may be increased beyond the two depicted in Figure 3 depending upon the requirements of the system.

In another preferred embodiment of the present invention, as depicted in Figure 4, a reformer 200 is illustrated having serial parallel flow with two cells in parallel. The locally perpendicular flow of feed gas and exhaust gas flows similarly to the reformer 100 of Figure 3, but instead of every other cell having reformer sections and burner sections with different flow directions and temperature-distributions, the cells are paired in groups of two, each having substantially identical flow directions and temperature distributions.

Cool feed gas enters the top of the reformer 200 at a pair of inlet ports 201a, 201b defining inlet port 201. The feed gas entering through inlet port 201a flows between a top sheet 217 and a first header sheet 202a which defines a first reformer section 203a. Feed gas flows through the first reformer section 203a and into the front manifold ports 210f, through a front interleaved manifold port 222f of a adjacent interleaved sheet 220, through a front manifold ports 210f of the next adjacent header sheet 202, and through a front interleaved manifold port 222f of the next interleaved sheet 220 and into a reformer section 203. The feed gas then flows through the reformer section 203c and into a rear manifold port 210b, through a rear interleaved manifold port 222b, through another rear manifold port 210b, and through another rear

interleaved manifold port 222b to reach the next reformer section 203e. The process continues based on the flow requirements of the system until it reaches a feed gas outlet port 205a.

At the same time, a second quantity of cool feed gas flows from inlet port 201b between the first header sheet 202a and the first interleaved sheet 220a that defines a second reformer section 203b. The second quantity of cool feed gas then flows through a front interleaved manifold port 222f of the first interleaved sheet 220a, through a front manifold ports 210f of the next adjacent header sheet 202, through a front interleaved manifold port 222f of the next adjacent interleaved sheet 220, and through a front manifold port 210f and into a reformer section 203d. The feed gas flows through reformer section 203d, through a rear manifold port 210b, through a rear interleaved manifold port 222b, through a rear manifold port 210b or the next adjacent interleaved sheet 202, through a rear interleaved manifold port 222b of the next adjacent interleaved manifold sheet 220, and into the next adjacent reformer section 203f. Depending upon the flow requirements of the system, the first and second quantity of feed gas may intermingle between the reformer sections 203a, 203b respectively by being injected into the same manifold ports 210 or interleaved manifold ports 220. Similarly, the feed gas could intermingle between reformer sections 203d and 203e, respectively, and every next adjacent pair thereafter. The flow process continues until the feed gas reaches feed gas outlet port 205b. Feed gas outlet port 205a and 205b define feed gas outlet 205, which

discharges heated reformed feed gas from the reformer 200.

At the same time cool feed gas is introduced through feed gas inlet port 201, heated burner gas is being introduced to the reformer 200 at burner gas inlet port 207. A first quantity of heated burner exhaust gas or partially or fully unreacted fuel and oxidant enters burner inlet port 207a between bottom sheet 209 and header sheet 202b, which defines a first burner section 213a. The heated burner gas flows across burner section 213a and enters left manifold port 210l, goes through left interleaved manifold port 222l, through left manifold port 210l of an adjacent header sheet 202, and through a left interleaved manifold port 222l of the adjacent interleaved sheet 220 and into the next burner section 213c. The burner gas then flows across the burner section 213c and enters right manifold port 210r, through right interleaved manifold port 222r, through right manifold port 210r, and through right interleaved manifold port 222r and into the next adjacent burner section 213f. This process continues until the burner gas reaches outlet port 211a.

At the same time, a second quantity of heated burner gas enters burner inlet port 207b and into burner section 213b defined by header sheet 202b and interleaved sheet 220. The burner gas proceeds through burner section 213b and enters the left interleaved manifold port 220l, through left manifold port 210l, through left interleaved manifold port 220l of the next adjacent interleaved sheet 220, and through left

manifold port 210l of the next adjacent header sheet 202 and into the next adjacent burner section 213d. The burner exhaust flows through the burner section 213d and into the right interleaved manifold port 222r, the right manifold port 210r, the next right interleaved manifold port 222r, and the next manifold port 210r and into the next burner section 213f. The process continues until the second quantity of burner gas reaches burner outlet port 211b. Outlet ports 211a and 211b form burner outlet port 211, which discharges cooled burner exhaust from the reformer 200.

It is contemplated that the first quantity of burner gas and the second quantity of burner gas may intermingle between burner sections 213a, 213b by using the same manifold ports 210, 222 located along the various sides of the header sheets 202 and interleaved sheets 220. Similarly, the reformer gas could intermingle between reformer sections 203d and 203e, respectively, and every next adjacent pair thereafter.

Further, it is contemplated in another preferred embodiment not depicted here that the serial cross-flow geometry could vary between 3, or even 4 sets of sheets or more depending upon the flow characteristics desired within the reformer, thereby reducing the peak Reynold's number. In addition, it is contemplated that the reformer could use a combination of embodiments as depicted in Figures 3 and 4, wherein the zones used within the reformer are varied between single zones of cross flow, as in Figure 3, and paired zones, as in Figure 4. Again, the specific combination

of these zones would depend upon the desired characteristics of the system.

Referring now to Figure 5, another embodiment of the present invention is depicted. In this embodiment, a reformer 300 is depicted having a mixture of serial flow zone reformers 301 and parallel flow zone reformers 302. The serial flow zone reformers 301, for example, may be similar to reformer 100 from Figure 3 or reformer 200 from Figure 4, and is depicted similar to reformer 100 for representative purposes in Figure 5. In the parallel-flow zone reformer 302 portion, a feed gas inlet port 304a and a feed-gas-outlet port 306a are introduced at opposite ends between the bottom sheet 309 of the serial cross-flow reformer 301 and a first header sheet 311a of parallel-flow reformer 302. A burner gas inlet port 308a and burner gas outlet port 310a is introduced between the first header sheet 311a and an interleaved sheet 313a. Another feed gas inlet port 304b and feed gas outlet port 306b may be introduced between interleaved sheet 313a and the next adjacent header sheet 311, while another burner gas inlet port 308b and burner gas outlet port 310b may be introduced between header sheet 311 and the next adjacent interleaved sheet 313. In this way, a reformer 300 can have mixtures of serial cross-flow and parallel-cross flow.

The exact mix of serial 301 and parallel zones 302 within reformer 300 would depend upon optimization based upon the system being investigated. Systems where exchanger mass, volume, and cost

predominate would tend to have a more highly serial architecture.

Plate-frame heat exchange reactors with serial cross-flow geometry according to the present invention offers many advantages over traditional massively parallel units.

First, the present invention allows for tailoring the Reynold's number of the flow to greatly improve the heat transfer and/or mass transfer characteristics of the reactor. This allows reactor size to be reduced by half or more, resulting in substantial savings in weight, volume, and cost.

Second, the present invention allows for the possibility of introducing reactants at many distributed points, rather than only at the entry point in massively parallel designs, using a simple mechanical feature added to the header sheets. This controls the formation of hot spots within the reactor that could lead to undesirable chemical reactions.

Third, the present invention offers greatly simplified manifolding of the flows and reduces the number of distinct components required for the heat exchanger. This results in substantial cost savings as compared with massively parallel designs.

Fourth, the heat exchanger plates are not constrained by a desire to create a high aspect ratio, perfect counterflow ratio in a single cell.

The application of the present invention is ideally suited for reaction systems where current,

massively parallel plate frame reactors are inadequate. One example is steam reforming of hydrocarbons or alcohols where reactor size is principally determined by heat transfer, and where controlled release of oxidant can greatly reduce the risk of hot spot formation. Another example is the preferential oxidation of carbon monoxide where close control of temperature, controlled oxidant release, and improved mass transfer are desired.

While the invention has been described in terms of preferred embodiments, it will be understood, of course, that the invention is not limited thereto since modifications may be made by those skilled in the art, particularly in light of the foregoing teachings.